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Feasibility study of spectral pattern recognition reveals distinct classes of volcanic tremor

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ABSTRACT

Systematic investigations of the similarities and differences among volcanic tremor at a range of volcano types may hold crucial information about the plausibility of inferred source mechanisms, which, in turn, may be important for eruption forecasting. However, such studies are rare, in part because of an intrinsic difficulty with identifying tremor signals within very long time series of volcano seismic data. Accordingly, we develop an efficient tremor detection algorithm and identify over 12,000h of volcanic tremor on 24 stations at Kīlauea, Okmok, Pavlof, and Redoubt volcanoes. We estimate spectral content over 5-minute tremor windows, and apply a novel combination of Principal Component Analysis (PCA) and hierarchical clustering to identify patterns in the tremor spectra. Analyzing several stations from a given volcano together reveals different styles of tremor within individual volcanic settings. In addition to identifying tremor properties common to all stations in a given network, we find localized tremor signals including those related to processes such as lahars or dike intrusions that are only observed on some of the stations within a network. Subsequent application of our analysis to a combination of stations from the different volcanoes reveals that at least three main tremor classes can be detected across all settings. Whereas a regime with a ridge of high power distributed over 1–2Hz and a gradual decay of spectral power towards higher frequencies is observed dominantly at three volcanoes (Kīlauea, Okmok, Redoubt) with magma reservoirs centered at less than 5km below sea level (b.s.l.), a spectrum with a steeper slope and a narrower peak at 1–2Hz is observed only in association with open vents (Kīlauea and Pavlof). A third regime with a peak at approximately 3Hz is confined to two stratovolcanoes (Pavlof and Redoubt). These observations suggest generic relationships between the spectral character of the observed signals and volcano characteristics such as magma viscosity, storage depths, and the physical properties of volcanic edifices. Similarities among the spectral patterns detected at stations 4km and 8–10km distance from the centers of volcanic activity, respectively, indicate that path effects do not strongly influence spectral shapes at distances of a few kilometers from the inferred source of the signals. Our preliminary work shows that a global comparison of tremor is feasible. Our results suggest that further work on data from a larger sample and diverse range of volcano types will reveal additional classes of tremor signals and plausibly identify fingerprints of source processes that are specific to volcano type, but independent of volcano location.

1. Introduction

Volcanic eruptions are often preceded and accompanied by a low-frequency (approximately 0.5–10 Hz) seismic signal called “volcanic tremor” (McNutt, 1992; Konstantinou and Schlindwein, 2002; McNutt and Nishimura, 2008), hereafter referred to as “tremor”. Tremor can persist for minutes to weeks and its occurrence is often interpreted as a sign of an impending eruption (e.g., D’Agostino et al., 2013; Chardot et al., 2015). The reliability of tremor as a forecasting tool is, however, uncertain, because the underlying physical processes remain unclear (Konstantinou and Schlindwein, 2002). Indeed, diverse tremor observations in different locations suggest that this oscillation may be the expression of a variety of mechanisms (e.g., Chouet, 1986; Julian, 1994; Benoit and McNutt, 1997; Ripepe and Gordeev, 1999; Neuberg et al., 2000; Lesage et al., 2006; Jellinek and Bercovici, 2011; Dmitrieva et al., 2013; Bean et al., 2014). However, systematic investigations of similarities and differences among tremor properties in different volcanic settings that could shed light on whether there exists a common set of source processes are rare (e.g., McNutt, 1994, 2004). Accordingly, we apply a

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new method to analyze spectral properties of tremor to address the following questions:

(1) Within a given volcanic setting:
  (a) Are there tremor signals with distinct spectral signatures (fingerprints)?
  (b) What are the spatio-temporal properties of such spectral fingerprints?
(2) Among several volcanic settings:
  (a) Is it feasible to identify spectral properties of tremor that are common to several volcanoes?
  (b) Are similarities in tremor properties among different settings related to the distinctive characteristics of the volcanoes (e.g., magma viscosity, edifice type, geometry of the plumbing system) and independent of volcano location?

To identify systematics we use pattern recognition to determine characteristic spectral shapes for tremor from four volcanoes with well-studied and strongly contrasting eruptions. In Section 2 we introduce each of the volcanic settings we analyze. In Section 3, we develop an algorithm to detect volcanic tremor in continuous seismic data on individual stations ("single station detection") and outline the preprocessing steps to obtain corresponding tremor spectra. These spectra are then analyzed with a recently developed pattern recognition approach that combines Principal Component Analysis (PCA) and hierarchical clustering (Section 4; Unglert et al., 2016). Finally, we discuss our observations, inferences, and potential implications for identifying and understanding underlying physical processes in Section 5.

2. Volcanic settings

We analyze time series of seismic data related to volcanic unrest from two shield volcanoes (Kīlauea, 2007–2011, and Okmok, 2008), and two stratovolcanoes (Pavlof, 2007 & 2013, and Redoubt, 2009). All datasets are from permanent networks, and all times are in UTC.

Kīlauea Volcano on the Big Island of Hawai'i is an intraplate shield volcano erupting mostly basaltic magmas (~49–50 wt % SiO_2, Garcia et al., 1989, 1992, Global Volcanism Program, 2013a). Our data include two time periods of dike intrusions and accompanying small fissure eruptions (19 June 2007 and 6–10 March 2011, Poland et al., 2008; Fee et al., 2011a; Orr et al., 2015), and a period of small explosive bursts during the formation of the summit lava lake in 2008 (Wilson et al., 2008; Houghton et al., 2013). All three episodes of volcanic activity are part of the ongoing eruptive sequence with a Volcanic Explosivity Index (VEI) of 1 (Global Volcanism Program, 2013a). A shorter version of the same dataset was analyzed extensively by Unglert and Jellinek (2015). We thus use it as a benchmark for the pattern recognition algorithm by Unglert et al. (2016) that has only been tested on synthetic data.

Okmok, Pavlof, and Redoubt are part of the Aleutian chain, a volcanic arc related to subduction of the Pacific Plate below the North American and Bering Sea plates (e.g., Buurman et al., 2014). Okmok is a shield volcano with volcanic activity focused in a complex of two overlapping calderas (Global Volcanism Program, 2013b). Our data from permanent stations operated by the Alaska Volcano Observatory span a large (VEI 4) phreatomagmatic explosive eruption between 12 July–19 August 2008 that produced dominantly andesite to basaltic andesite (~51–57 wt % SiO_2) and a series of lahars (Larsen et al., 2009,2013, 2015).

Pavlof Volcano is a stratovolcano close to the western end of the Alaska Peninsula with mostly Strombolian to Vulcanian activity and andesite to basaltic andesite magmas (~53–58 wt % SiO_2, Waythomas et al., 2014, 2008; Mangan et al., 2009; McGimsey et al., 2011). Two eruptions are included in our analysis: A VEI 2 eruption on the southeastern flank between 14 August–13 September 2007 (Waythomas et al., 2008), and a VEI 3 eruption on the northwestern flank between 13 May–1 July 2013 (Waythomas et al., 2014). In addition to explosive activity and ash emission, both eruptions included lava fountaining, spatter flows, and lahars on the slopes of the cone (Waythomas et al., 2014).

At Redoubt Volcano, an andesitic stratovolcano at the northeastern end of the arc, a VEI 3 eruptive period between 15 March to approximately 1 July 2009 included phreatic and magmatic explosions (e.g., Bull and Buurman, 2012), as well as the effusion and destruction of several lava domes and associated lahars (Schaefer, 2011; Diefenbach et al., 2013). Our data include a period of precursory seismicity (Schaefer, 2011; Power et al., 2013) in addition to the main eruptive phases. The eruption produced mainly andesite with 57–63 wt % SiO_2 (Schaefer, 2011; Coombs et al., 2013).

3. Data and preprocessing

We combine continuous, vertical component seismic data from short-period sensors from the permanent networks at the volcanoes introduced in Section 2. All stations are Mark Products L-4 seismometers with a 1 Hz corner frequency and sampled at 100 Hz. The only exceptions are stations PV6 at Pavlof and REF at Redoubt, which are Mark Products L22D seismometers with a 2 Hz corner frequency and sampled at 100 Hz. All of the time periods include at least one discrete eruptive event, or are part of an ongoing eruptive phase. We select these volcanoes on the basis of data availability, the detection of volcanic tremor and to cover a large range of volcano types, magma compositions, and eruptive activity. We restrict our analysis to stations that recorded seismicity associated with the eruptive episodes approximately continuously without any technical issues. We perform an instrument response correction to achieve a flat response between 0.5–15 Hz. Whereas short-period sensors are common in volcano monitoring and thus used here, the algorithm is generally applicable also to data from broadband stations.

3.1. Distinguishing tremor from the background

To reduce the amount of data to be analyzed, we develop an algorithm to detect periods of strong volcanic tremor. In our examples, we define tremor as elevated seismic amplitude compared to the background at each station, sustained over durations much longer than typical local earthquake durations (usually up to 10s of seconds, e.g., Gómez and Torres, 1997; Ketner and Power, 2013). Different tremor definitions are possible and might, for example, require analyzing all data, or using much shorter or longer time windows. However, for the scope of this study, we choose a value of 5 min for the length of the time window, similar to studies of tectonic tremor (e.g., Wech and Creager, 2008). However, tests with shorter (3 min) and longer (10 min) durations give qualitatively similar results. To identify high amplitudes, we take the following approach:

1. Estimate median absolute background amplitude.
2. Divide continuous seismic data into non-overlapping 5-minute windows.
3. Compare median absolute amplitude over each window to median absolute background amplitude.

We introduce the no-overlap criterion (2.) to avoid counting tremor episodes twice. We use the median in all cases to reduce the influence of a few large spikes within any given window. To determine the median absolute background amplitude, we obtain the background spectrum by identifying the minimum spectral power value at each frequency over time (Vila et al., 2006) (Fig. 1 (a) and (c)). The main idea behind this method is that if the time period analyzed is longer than the period of volcanic unrest, then the process(es) driving oscillations at a given frequency observed during unrest will

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